

# Observation of two-photon interference with temporally non-overlapping coherent pulses

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We report experiments on two-photon interference between temporally non-overlapping weak coherent pulses. While the single-photon interference is washed out, the two-photon interference shows a Hong-Ou-Mandel dip with visibility of  $0.50 \pm 0.09$ , which shows that the two-photon classical interference does not require temporal overlapping between optical pulses.

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Interference is one of the most interesting phenomena in nature for many physicists. Since the first experimental demonstration of optical interference by Young [1], it has been considered one of the most important notions for understanding optics [2]. Classically, it is understood as a coherent superposition of electromagnetic waves, and it explains, in classical terms, many interesting phenomena. For example, one of the outputs of a Mach-Zehnder (MZ) interferometer shows a sinusoidal oscillation with respect to the relative phase difference between two inputs and this phenomenon can be fully explained by classical theory.

Classical physics, however, cannot sometimes fully describe interference. Let us consider a Hong-Ou-Mandel (HOM) interference between two identical photons [3–5]. When two identical photons enter into a beamsplitter (BS) at the same time, the coincidences between two detectors at the outputs of the BS are completely suppressed, a characteristic referred as a HOM dip. The visibility,  $V$ , of the HOM dip is defined as the relative depth of the dip compared to the non-interfering cases. Using single-photon states, the coincidences can be completely suppressed, so the visibility can reach up to  $V = 1$ . The classical theory of the coherent superposition of electromagnetic waves, however, can only explain a HOM dip with  $V \leq 0.5$  [6]. Thus, a HOM dip with  $V > 0.5$  should be considered as a non-classical phenomenon, and therefore a quantum effect described by a superposition of indistinguishable probability amplitudes [7].

In many experimental demonstrations with light pulses, classical and quantum interference are measured when pulses have temporal overlap at a BS [8–10]. It often leads to a common misconception that classical and/or quantum interference requires the optical pulses to be temporally overlapping. However, it has been shown that temporal overlapping between optical pulses is not a requirement for quantum interference; Both single- and two-photon quantum interference

can occur from temporally non-overlapping single-photon states [11–15]. In these papers, the authors clearly explain the phenomena in terms of quantum physics and the superposition of probability amplitudes with Feynman diagrams [7].

In classical physics, however, the superposition of probability amplitudes and Feynman diagrams are not applicable. Instead, the classical electromagnetic waves superposition theory should be employed to describe the interference. It is easy to think that there would be no interference between two temporally non-overlapping optical pulses because it seems that the electromagnetic waves do not exist without an optical pulse.

In this Letter, we show that the classical interference actually occurs between two temporally non-overlapping optical pulses. In particular, we report experimental observation of HOM-type two-photon classical interference between two temporally non-overlapping weak coherent pulses. The result can be explained by the classical theory of waves superposition. We also provide a quantum analogy to this phenomenon for more intuitive understanding.

Figure 1 shows the schematic of our two-photon interference experiment with weak coherent pulses,  $I_A(i)$ ,  $I_A(j)$ ,  $I_B(i)$ , and  $I_B(j)$ . Here,  $i, j$  denote the timing labels and the subscripts  $A, B$  are the input modes. The intervals between  $I_k(i)$  and  $I_k(j)$  for both  $k = A, B$  are the same,  $T$ . The optical delay between two inputs,

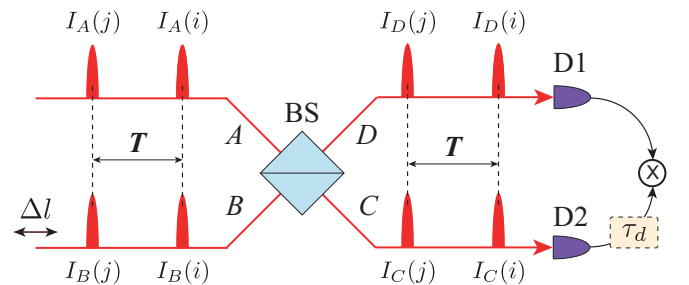


FIG. 1. The schematic of Hong-Ou-Mandel interference with four weak coherent pulses.

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$\Delta l = I_A(i) - I_B(i)$ , can be scanned for the interference measurement. Note that the interval between  $I_B(i)$  and  $I_B(j)$  is fixed at  $T$  during the scanning. We will only consider the case that the scanning of  $\Delta l$  is much smaller than  $T$ , so it does not provide temporal overlap between two different labeling pulses, e.g., between  $I_A(i)$  and  $I_B(j)$ . The intensities at the BS outputs  $I_C(i)$  and  $I_D(i)$  are

$$\begin{aligned} I_C(i) &= \frac{1}{2}I_A(i) + \frac{1}{2}I_B(i) - \sqrt{I_A(i)I_B(i)} \sin \Delta\phi(i) \\ I_D(i) &= \frac{1}{2}I_A(i) + \frac{1}{2}I_B(i) + \sqrt{I_A(i)I_B(i)} \sin \Delta\phi(i), \end{aligned} \quad (1)$$

where  $\Delta\phi(i)$  denotes the relative phase between two pulses  $I_A(i)$  and  $I_B(i)$ . The relative phase can be represented as

$$\Delta\phi(i) = \Delta\phi_{AB}(i) + \frac{2\pi\Delta l}{\lambda}, \quad (2)$$

where  $\Delta\phi_{AB}(i)$  represents the inherent phase difference between two pulses  $I_A(i)$  and  $I_B(i)$  and  $\lambda$  is the wavelength of the light.

When two pulses  $I_A(i)$  and  $I_B(i)$  are coherent, that is  $\Delta\phi_{AB}(i)$  has a fixed definite value, Eq. (1) shows sinusoidal interference which corresponds to a single-photon interference, i.e., Mach-Zehnder like interference. However, if the two pulses are incoherent, and thus  $\Delta\phi_{AB}(i)$  varies randomly, the single-photon interference will be washed out since  $\langle \sin \Delta\phi(i) \rangle = 0$ , where  $\langle x \rangle$  represents the average of  $x$  over many events.

The coincidences between D1 and D2 correspond to the correlation measurement between  $I_C$  and  $I_D$  for low input intensities  $I_A$  and  $I_B$ . Let us first consider the correlation measurement between two pulses at the same timing,  $\langle I_C(i)I_D(i) \rangle$ . Note that this case is equivalent to a standard HOM interferometer with coherent pulses as the two pulses meet at the BS. It is easily accomplished in the experiment by putting a zero-electronic delay at D2,  $\tau_d = 0$  as depicted in Fig. 1. Since  $\langle \sin \Delta\phi(i) \rangle = 0$  for a randomized  $\Delta\phi(i)$ , the correlation measurement is represented by [6]

$$\langle I_C I_D \rangle = \frac{1}{4}\langle I_A^2 \rangle + \frac{1}{4}\langle I_B^2 \rangle + \left( \frac{1}{2} - \langle \sin^2 \Delta\phi \rangle \right) \langle I_A \rangle \langle I_B \rangle. \quad (3)$$

Here, we omitted the label  $i$  in Eq. (3). The  $\langle \sin^2 \Delta\phi \rangle$  term vanishes for the interference free case. In the interference case,  $\langle \sin^2 \Delta\phi \rangle = 1/2$ , thus the whole last term of Eq. (3) disappears. Therefore, the visibility of the two-photon interference in classical physics is

$$V_c = \frac{2\langle I_A \rangle \langle I_B \rangle}{\langle I_A^2 \rangle + \langle I_B^2 \rangle + 2\langle I_A \rangle \langle I_B \rangle}. \quad (4)$$

For constant intensities  $\langle I_k^2 \rangle = \langle I_k \rangle^2$ , the maximum classical visibility is  $V_c^{\max} = 0.5$  when  $\langle I_A \rangle = \langle I_B \rangle$ . This result is the classical limit of a HOM interference.

Now, let us consider the correlation measurement between pulses which did not exist at the same time, i.e.,  $\langle I_C(i)I_D(j) \rangle$  where  $i \neq j$ . Note that the nonzero electronic delay of  $\tau_d = T$  will satisfy this condition. Noting that  $\langle \sin \Delta\phi(i) \rangle = \langle \sin \Delta\phi(j) \rangle = 0$ , the correlation measurement can be represented by

$$\begin{aligned} \langle I_C(i)I_D(j) \rangle &= \frac{1}{4}\langle I_A(i)I_A(j) \rangle + \frac{1}{4}\langle I_A(i)I_B(j) \rangle + \frac{1}{4}\langle I_B(i)I_A(j) \rangle + \frac{1}{4}\langle I_B(i)I_B(j) \rangle \\ &\quad - \sqrt{\langle I_A(i)I_A(j)I_B(i)I_B(j) \rangle} \langle \sin \Delta\phi(i) \sin \Delta\phi(j) \rangle. \end{aligned} \quad (5)$$

In general,  $\langle \sin \Delta\phi(i) \sin \Delta\phi(j) \rangle = 0$ , thus, Eq. (5) does not show interference. However, let us consider the case when intensities of two pulses are the same at the same input and also they are coherent. Then, one can find the following conditions are satisfied:

$$\begin{aligned} I_k(i) &= I_k(j) \\ \Delta\phi(i) &= \Delta\phi(j). \end{aligned} \quad (6)$$

Note that the second condition is satisfied if  $\Delta\phi_{AB}(i) = \Delta\phi_{AB}(j)$ . It is important to remember that although  $\Delta\phi(i) = \Delta\phi(j)$ , the values are still randomly varying. These conditions can be obtained from, for example, mode-locked laser pulses. With these conditions, Eq. (5) transforms to Eq. (3), and therefore the two-photon interference with  $V = 0.5$  will be measured.

It is notable that all the events registered as the coincidences for this case come from two temporally separated coherent pulses, one at  $i$  and the other at  $j$ . It seems natural that when there is no overlap between optical pulses, the electromagnetic waves are also not overlapped, i.e., no superposition. This intuition, however, is incorrect as indicated by the last term of Eq. (5). This interference term contains all four intensities of input pulses, thus, shows all electromagnetic waves interfere although there is no optical pulse overlapping. In short, in the classical view of interference, the electromagnetic waves are responsible for the interference, not the photons [16].

Because classical physics is a subset of quantum physics, one should be able to explain the interference with temporally non-overlapping coherent pulses with

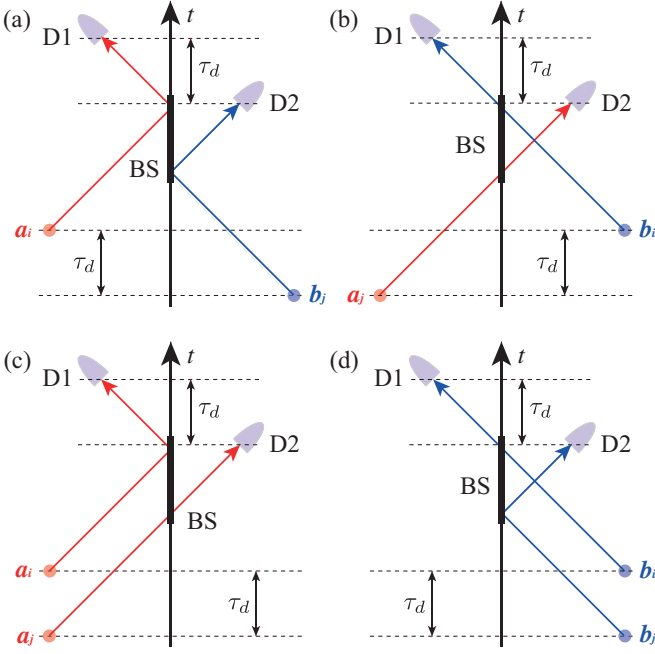


FIG. 2. Feynman diagrams for  $\Delta l = 0$ . In general, all (a)-(d) cases are distinguishable, so they do not interfere. However, when pulses in the same inputs (between  $a_i$  and  $a_j$ , for example) are coherent, (a) and (b) become indistinguishable, so they interfere. For single-photon pulses, one can effectively suppress (c) and (d) while maintaining the coherence, so one can measure a  $V = 1$  HOM dip with temporally non-overlapping pulses. For classical optical pulses such as coherent states, however, one cannot remove cases (c) and (d) without disturbing the coherence, so the maximum visibility is limited to 0.5.

quantum descriptions. Moreover, quantum descriptions are usually more intuitive, so one can more easily understand the physics behind. Therefore, let us consider quantum interpretations of the phenomenon with Feynman diagrams. Since the coincidences are registered by two-photons separated by  $T = \tau_d$ , there are four possible biphoton amplitudes as depicted in Fig. 2. Here,  $a$  and  $b$  denote the annihilation operators at input  $A$  and  $B$ , and the subscripts  $i$  and  $j$  are the labeling parameters. Although the Feynman diagrams are depicted with single-photon states, it is still applicable for our case since the coherent pulses are so weak that they mostly contain only a single photon and also when more than two-photons exist at the same time, they do not lead to relevant coincidences.

In general, all four cases are distinguishable, so they do not interfere. However, when  $a_i$  and  $a_j$  are coherent and  $b_i$  and  $b_j$  are also coherent, Fig. 2 (a) and (b) become indistinguishable, so they do interfere. Because half of the cases interfere while the other half does not, the expected visibility will be 0.5.

This quantum description raises an interesting question: If coherent pulses only exist in the cases shown in

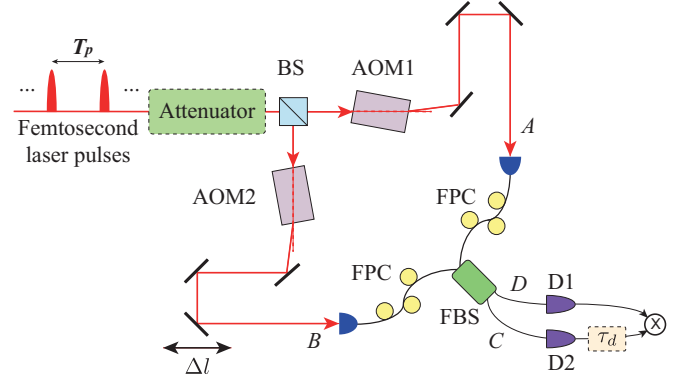


FIG. 3. Experimental setup. BS: beam splitter, AOM: acousto-optic modulator, FPC: fiber polarization controller, FBS: fiber beamsplitter, D1 and D2: single photon detectors. The AOMs are used for the phase randomization between two arms.

Fig. 2 (a) and (b), do they show  $V = 1$  two-photon interference? The answer to this question is that it is impossible to remove the other cases (Fig. 2 (c) and (d)) while maintaining the coherence between pulses in the same inputs unless the optical pulses are single-photon states [17, 18]. Thus, even with the quantum description, the classical visibility is limited to 0.5.

Figure 3 shows our experimental setup. Femtosecond laser pulses from a mode-locked Ti:Sapphire laser is used for the experiment. Note that the pulse train and the electronic delay  $\tau_d = T = mT_p$  where  $T_p$  and  $m$  are the pulse period and an integer, respectively, will implement Fig. 1. The central wavelength and the spectral bandwidth of the pulses are 780 nm and 15 nm, respectively. The repetition rate of the pulses is 85 MHz, so the interval between adjacent pulses  $T_p \approx 11.8$  ns, which corresponds to 3.5 m in space. The attenuator is introduced to reduce the average photon number per pulse.

A BS splits the incoming pulses into two paths. Each pulse enters into acousto-optic modulators (AOM1 and AOM2) and the deflected pulses are collected by single-mode optical fibers at inputs  $A$  and  $B$ . After the fiber polarization controllers (FPC), that make the polarization identical, the incoming pulses interfere at the fiber beam splitter (FBS). The optical path delay  $\Delta l$  is scanned by a translation stage placed at input  $B$ . A typical scanning range for  $\Delta l$  is hundreds of  $\mu\text{m}$  which is much smaller than  $T_p$ , so the scanning of  $\Delta l$  does not provide temporal overlap between adjacent pulses. Silicon avalanche photodiode based single photon detectors D1 and D2 are placed at the outputs of FBS, and a variable electronic delay  $\tau_d$  is introduced at D2.

The phase randomization between inputs  $A$  and  $B$  can be accomplished with the help of two AOMs modulated by two independent radio frequency (RF) drivers. An AOM adds additional phase to the deflected beam relative to the driving RF signal. Thus, if the RF signals

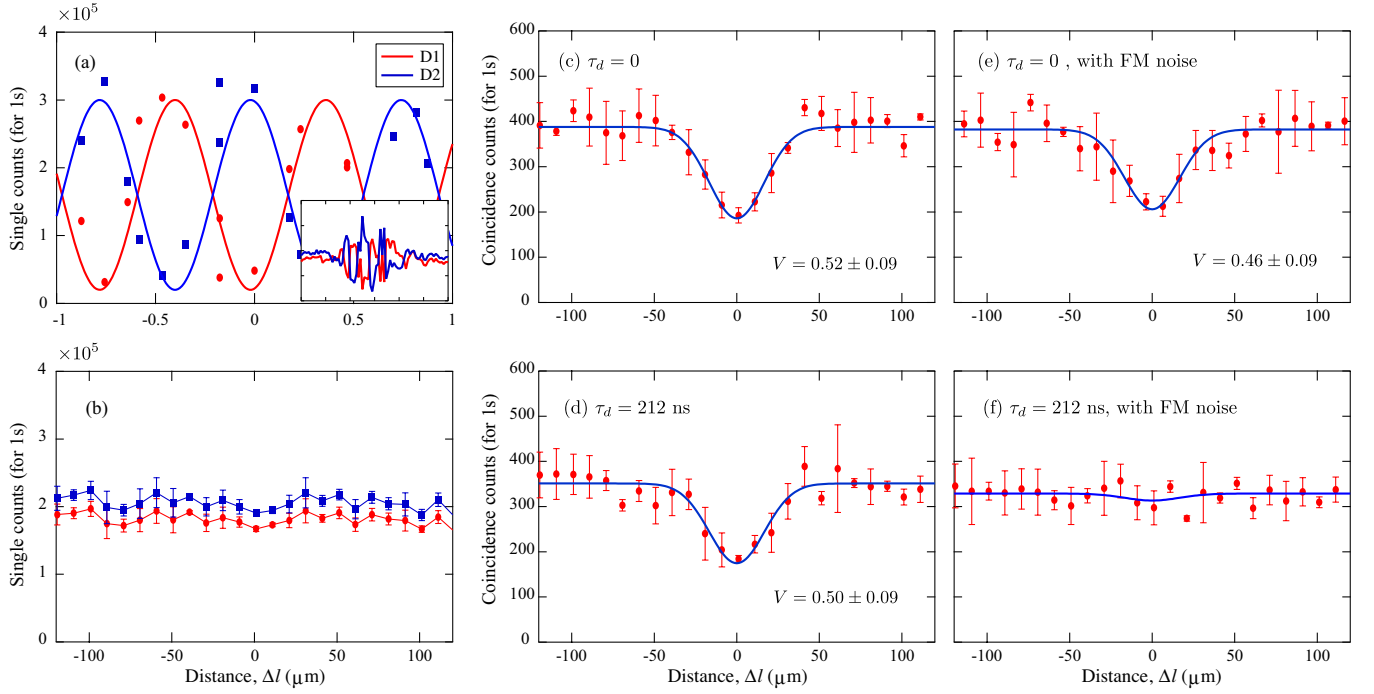


FIG. 4. Single and coincidence counts for various conditions. Single and coincidence counts are proportional to  $\langle I_C \rangle$  ( $\langle I_D \rangle$ ) and  $\langle I_C I_D \rangle$ , respectively. Error bars are the experimentally obtained standard deviations. The single counts when RF signals to AOM1 and 2 are (a) synchronized and (b) independent. The inset of (a) shows the envelop of the single-photon interference. (c)-(f) coincidence counts between D1 and D2. (c)  $\tau_d = 0$ . (d)  $\tau_d = 212$  ns. (e), (f)  $\tau_d = 0$  and  $\tau_d = 212$  ns with an additional noise input to the FM input of the RF driver to AOM1. Estimated visibilities are also shown. (c) and (e) correspond to a HOM interference with classical pulses so a standard HOM dip is observed. (d) and (f) correspond to the two-photon interference between temporally non-overlapping optical pulses.

are unsynchronized, two AOMs will wash out the phase relation between the two inputs. It is experimentally verified by applying either synchronized (see Fig. 4 (a)) or independent (see Fig. 4 (b)) RF signals. While the synchronized RF signals maintain the single-photon interference as they conserve the phase relation between  $A$  and  $B$ , the independent RF signals completely suppress the phase interference. Note that for the independent RF signals, the RF frequencies are still almost the same, 40 MHz.

After we confirmed the phase randomization between  $A$  and  $B$ , we measured coincidence counts between D1 and D2. The result with  $\tau_d = 0$  is shown in Fig. 4 (c). It shows a clear HOM interference with visibility  $0.52 \pm 0.09$  which is consistent to the classical limit of HOM interference visibility. Note that this case corresponds to a standard HOM interference with temporally overlapped coherent pulses.

Fig. 4 (d) shows the two-photon interference between temporally non-overlapped coherent pulses. Here, the electronic delay  $\tau_d = 212$  ns, so  $m = 18$  was chosen. The data shows a clear two-photon interference with  $V = 0.50 \pm 0.09$ . The mode-locked laser pulse train satisfies the condition of Eq. (6), and thus shows the same two-photon interference as the temporally overlapped pulses.

To see how the two-photon interference changes when coherence between pulses at the same inputs is not maintained anymore, so the condition of Eq. (6) fail. In order to disturb the coherence, we input fast random noise to the frequency modulation (FM) input of one of the AOM RF drivers. The random noise produces random frequency deviations of  $\pm 50\%$  to the RF signal, so the coherence between pulses at the same input will be degraded when  $\tau_d$  is sufficiently large. This will cause  $\Delta\phi_{AB}(i) \neq \Delta\phi_{AB}(j)$ , thus  $\Delta\phi(i) \neq \Delta\phi(j)$ . Note that the amount of the frequency deviation is much smaller than the spectral bandwidth of the coherent pulses, so the interference degradation due to the frequency mismatch is negligible.

The coincidence counts with FM noise input are depicted in Fig. 4 (e) and (f) for  $\tau_d = 0$  and 212 ns, respectively. For the case of  $\tau_d = 0$ , the experiment corresponds to a standard HOM interferometer with two temporally overlapping coherent pulses, so we observe the HOM dip with classical visibility limit. The measured visibility is  $0.46 \pm 0.09$ . When  $\tau_d = 212$  ns, however, the two-photon interference is eliminated as the FM noise diminishes the coherence between pulses at the same input.

To summarize, we reported two-photon interference with weak coherent pulses from a single laser. While

the single-photon interference was erased by two AOMs modulated by independent RF signals, the two-photon interference with  $V = 0.5$  was still measured. We observed the same two-photon interference with two temporally separated coherent pulses, thus, clearly verifying that *classical* two-photon interference does not require the temporal overlapping of photons. We also showed that coherence between coherent pulses at the same inputs is essential for the two-photon interference with temporally non-overlapping weak coherent pulses.

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- [1] T. Young, *Lectures on natural philosophy* (Johnson, London, 1807), Vol. I, p. 464.
  - [2] E. Hecht, *Optics* (Addison-Wesely, 2002)
  - [3] C.K. Hong, Z.Y. Ou and L. Mandel, Phys. Rev. Lett. **59**,

- 2044 (1987).
- [4] Y.H. Shih and C.O. Alley, Phys. Rev. Lett. **61**, 2921 (1988).
- [5] Z.Y. Ou and L. Mandel, Phys. Rev. Lett. **61**, 50 (1988).
- [6] J.G. Rarity, P.R. Tapster, and R. Loudon, J. Opt. B: Quantum Semiclass. Opt. **7**, S171 (2005).
- [7] R.P. Feynman, *QED The strange theory of light and matter* (Princeton University Press, Princeton, NJ, 1985).
- [8] L. Mandel, Rev. Mod. Phys. **71**, S274 (1999).
- [9] Y.-S. Kim, H.-T. Lim, Y.-S. Ra, and Y.-H. Kim, Phys. Lett. A **374**, 4393 (2010).
- [10] Y.-S. Kim, *et al.*, Opt. Express **19**, 24957 (2011).
- [11] T.B. Pittman, *et al.*, Phys. Rev. Lett. **77**, 1917 (1996).
- [12] Y.-H. Kim, M. V. Chekhova, S.P. Kulik, and Y. Shih, Phys. Rev. A **60**, R37 (1999).
- [13] Y.-H. Kim, *et al.*, Phys. Rev. A **61** 051803(R) (2000).
- [14] Y.-H. Kim, Phys. Lett. A **315**, 352 (2003).
- [15] Y.-H. Kim and W.P. Grice, J. Opt. Soc. B **22**, 493 (2005).
- [16] L. de Broglie, and J.A.E. Silva, Phys. Rev. **172**, 1284 (1968).
- [17] L. Mandel, Phys. Rev. A **28**, 929 (1983).
- [18] Z.Y. Ou, Phys. Rev. A **37**, 1607 (1988).